Determining Voltage Stability Margin Values by Measuring the Hypotenuse Under PV and QV Curves

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Abstract – *Voltage instability is one of the main causes of electrical power system blackouts all around the world. Voltage instability can be analyzed with the used of PV and QV curves technique. From these curves, the values of voltage stability margin (VSM) can be determined. VSM is very important in analyzing voltage instability because it shows the distance of how far the power system is able to run before experiencing voltage instability. This paper presents the calculation of VSM values by measuring the hypothenuse under the PV and QV curves. These VSM values are used to determine the weakest bus in the power system. Then, these values are compared with the VSM values that are being calculated using the conventional equation. The IEEE 14-bus power system has been chosen as the reference electrical power system.*

Keywords: *Voltage instability analysis; Voltage stability margin; PV and QV curves; IEEE 14-bus power system*

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I. Introduction

Since the 1920s, the instability of electrical power system has been recognized as one of the main problems in power systems operation [1]. Voltage instability in one of the categories that falls under electrical power system instability. Previous events of blackouts occurred around the world show that voltage instability is one of the main cause of power system blackouts [2–6]. Voltage instability can be defined as the failure of an electrical power system to sustain the voltage magnitudes at all buses remain the same after the electrical power system is being exposed to a disturbance [7–9]. It occurs due to the failure of the electrical power system to supply ample power to cover the increased demand of load. Currently, the increase in electrical power demand has forced the operation of electrical power systems to operate very close to the instability limits [10,11]. Therefore, the analysis of voltage instability in electrical power systems is of paramount importance so that the electrical power systems always operate within the allowable range (far from the instability limit).

Most of the literatures [2,12–14] have stated that one of the most common methods of voltage instability analysis is the power-voltage (PV) curve and reactive power-voltage (QV) curve method. These curves can be generated by generating a series of power flow. For every series of power flow, the load of the electrical power system is increased until the point where the system is not able to operate any longer. The variation values of real power (P) and reactive power (Q) with the value of load is plotted as the PV and QV curve, respectively. Both PV and QV curves give the values of voltage stability margin (VSM). VSM values are very important because they point out the distance of how far the power system is able to run before experiencing voltage instability [7,15,16]. A weak bus is a bus that is closed towards experiencing voltage instability [17]. It cannot afford a large increase of load demand especially reactive power (Q) of load [18,19].

Lower value of VSM conveys that the closer of the bus towards experiencing voltage instability and vice versa. The expression to calculate the VSM by following [9,15,20] is given as,

$$VSM = \frac{V_{initial} - V_{critical}}{V_{critical}}, \qquad (1)$$

Where
$V_{initial}$ and $V_{critical}$ is the bus voltage at initial and critical operating point, respectively.

Note that (1) did not take the load increment values into account. This will result in the possibility of two load buses with dissimilar situation (one strong/stable bus and another bus is weak bus) to have a same or close VSM value. For instance, assume that there are two load buses namely Bus X and Bus Y in a power system. Both Bus X and Bus Y have the same value of $V_{initial}$ and $V_{critical}$ which are 1.0 per unit and 0.6 per unit, respectively. Based on (1) both Bus *X* and Bus *Y* will have the same VSM value which is 0.67 per unit. However, the load increment value at Bus *X* is 10 times the initial load value before reaching $V_{critical}$ value (0.6 per unit). On the other hand, the load at Bus Y can only be increase 4 times before reaching $V_{critical}$ value (0.6 per unit). This means that Bus *Y* is closer towards experiencing voltage instability compared to Bus *X* even though they both have the same VSM value. To overcome this issue, the VSM values in this research will be calculated by measuring the hypotenuse distance of the triangle under the PV and QV curves.

II. Methodology

A. Generation of PV and QV Curves

The methodological steps of plotting the PV and QV curves for the load buses are listed as follows [8,21]:

i. Run the power flow for the electric power system (IEEE-14 bus in this paper) by using Power World Simulator.
ii. Increase the value of P load at the load bus by 0.1 per unit in order to plot PV curve. Similarly, increase the value of Q load by 0.1 per unit in order to plot QV curve. Then run the power flow program again. A new voltage value at the selected bus will be obtained. Record the values of P or Q and the corresponding load bus voltage values.
iii. Repeat step (ii) until the value of desired P or Q cannot be delivered by the system.
iv. Lastly, use all the recorded value of P or Q obtained in previous steps and plot it against the voltage values of the selected load bus.

In this research, the incremental values of P of load (*ΔP*) and Q of load (*ΔQ*) to the system experiencing voltage instability are recorded. This is to identify the relationship between the VSM values with the load increment values.

B. Voltage Stability Margin

VSM can be defined as the distance between the initial voltage operating point until the voltage critical point [22]. Based on this definition, VSM should be calculated by measuring the hypotenuse distance of a triangle that can be formed under the PV and QV curves as shown in Fig. 1 and Fig. 2 [15,22]. VSM can be divided into two categories. The first one is VSM for real power of load (P) and the second one is VSM for reactive power of load (Q) which is denoted as *VSM (P)* and *VSM (Q)*, respectively. *VSM (P)* is available from the PV curve as shown in Fig. 1. Let $V_{Pinitial}$ and $V_{Pcritical}$ is the bus voltage at initial and critical operating point, respectively. Let also $P_{critical}$ and $P_{initial}$ is the value of real power of load at voltage critical point and initial operating point, respectively. Hence, *VSM (P)* can be calculated as

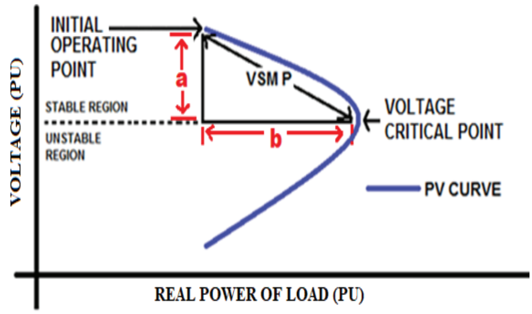

Fig. 1. *VSM (P)* in PV Curve

$$VSM\ (P) = \sqrt{a^2 + b^2}, \tag{2}$$

where $a = V_{Pinitial} - V_{Pcritical}$ and $b = P_{initial} - P_{critical}$. Note that *ΔP* is the highest value of *P* load that can be achieved before the system facing voltage instability. Thus, *ΔP* is given by

$$\Delta P = P_{critical} - P_{initial}. \tag{3}$$

Similarly, *VSM (Q)* is obtained from the QV curve as displayed in Fig. 2. Let $V_{Qinitial}$ and $V_{Qcritical}$ is the bus voltage at initial operating point and critical point, respectively. Let also $Q_{initial}$ and $Q_{critical}$ is the value of reactive power of load at initial operating point and voltage critical point, respectively. Hence, *VSM (Q)* can be calculated as

$$VSM\ (Q) = \sqrt{c^2 + d^2} \tag{4}$$

where $c = V_{Qinitial} - V_{Qcritical}$ and $d = Q_{initial} - Q_{critical}$. Note that *ΔQ* is the highest value of Q load that can be achieved before the system facing voltage instability. Hence, *ΔQ* can be determined as

$$\Delta Q = Q_{critical} - Q_{initial} \tag{5}$$

It is very clear from both Fig. 1 and Fig. 2 that smaller VSM values will cause the distance between the load buses towards voltage instability becomes closer and vice versa.

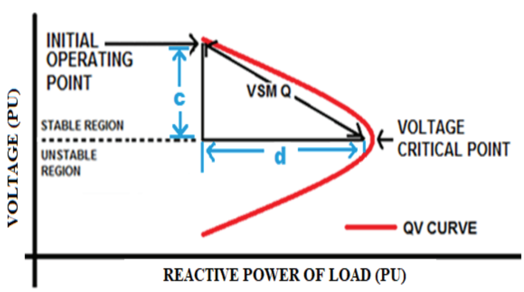

Fig. 2. *VSM (Q)* in QV Curve

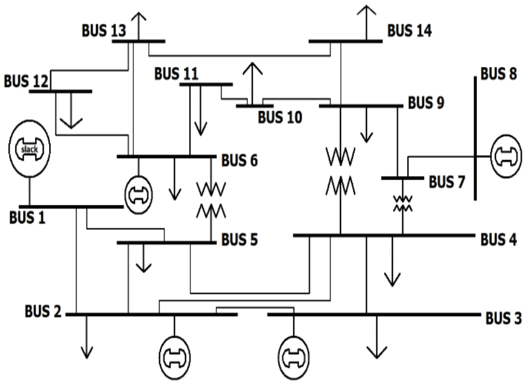

Fig. 3. IEEE 14-bus system

C. The IEEE 14-bus System

Fig. 3 shows the IEEE 14-bus system [23]. In this system, Bus 1 is the slack bus, Bus 2, Bus 3, Bus 6 and Bus 8 are the voltage-controlled buses, and the remaining buses (Bus 4, Bus 5, Bus 7 and Bus 9 until Bus 14) are the load buses. Load buses is very important in voltage stability analysis because PV and QV curve are generated at load buses. The load flow analyses are done by using Power World Simulator software version 16. In this research, only constant power load are considered since this type of load is favourable to voltage instability [8].

III. Results and Discussion

Table 1 lists the *VSM (P)* values calculated by using both the conventional equation that is based on (1) and by measuring hypotenuse under PV curve. These *VSM (P)* values are also compared with the incremental values of P load (ΔP). *ΔP* stands for the maximum value of P load that can be increased before the system experiencing voltage instability. To facilitate the observation process, Fig. 4 illustrates the ΔP from the lowest to the highest value.

From Table I and Fig. 4, it indicates that Bus 14 has the lowest value of *ΔP* compared to the rest of the buses. This means Bus 14 is the weakest bus in the IEEE-14 bus system. The weakest bus means that the bus has the highest tendency towards experiencing voltage instability since it cannot afford high incremental value of P load. In addition, the P modal analysis technique that has been done in the previous research work [24] has also shown that Bus 14 has the highest tendency towards experiencing voltage instability compared to other buses in the system. Hence, more attention should be given to Bus 14 to make sure that it does not reach the voltage instability limit. Fig. 5 depicts *VSM (P)* values calculated by using Equation 1 in an ascending order.

As can be seen in Fig. 5, Bus 13 is the weakest bus since it has the lowest *VSM (P)* value. It is also noticeable from Fig. 5 that Bus 14 is considered of one of the most stable bus in the IEEE-14 bus system. This is in contrast with the values of *ΔP* stated in Table 1 and Fig. 4. Besides that, Fig. 5 also depicts that the *VSM (P)* value of Bus 4 is similar to the *VSM (P)* value of Bus 14. Whereas, from Fig. 4, Bus 4 can afford a huge amount of *ΔP* value. This indicates that the *VSM (P)* values calculated by using the conventional equation based on (1) are not in synchronisation with the values of *ΔP*. Fig. 6 depicts *VSM (P)* values that is calculated by measuring the hypotenuse under the PV curve in an ascending order.

Fig. 6 depicts that Bus 14 is the weakest bus in the IEEE-14 bus system since it has the lowest *VSM (P)* value. This is in similar with the results in Fig. 4 and results in [24]. In addition, it is observable from Fig. 6 that the ranking of the load buses from the weakest to the strongest are same with the ranking in Fig. 4. This proves that the *VSM (P)* values calculated by measuring hypotenuse under PV curve are in synchronisation with the values of *ΔP*.

TABLE I
VALUES OF *ΔP* AND *VSM (P)*

Bus	*ΔP* (per unit)	*VSM (P)* based on (1)	*VSM (P)* by measuring the hypotenuse under the PV curve
4	2.9	0.4531	2.9173
5	3.3	0.5354	3.2961
7	1.6	0.3237	1.6209
9	1.4	0.3220	1.4234
10	1.2	0.3574	1.2315
11	1.1	0.3304	1.1309
12	0.9	0.5331	0.9713
13	1.0	0.2530	1.0222
14	0.8	0.4678	0.8654

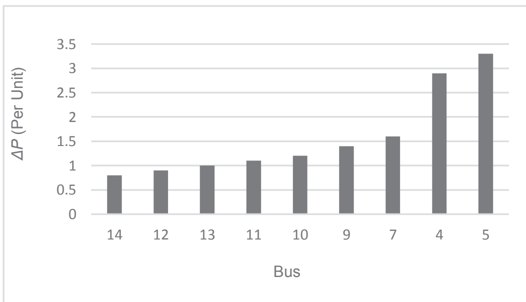

Fig. 4. The maximum value of P load that can be increased before experiencing voltage instability

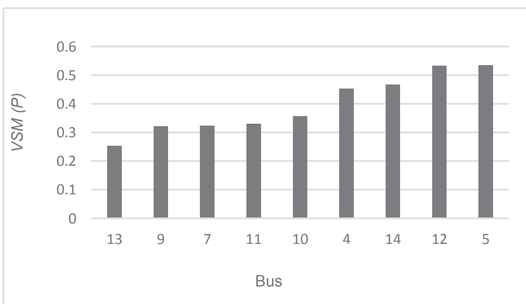

Fig. 5. *VSM (P)* Values by Using Equation 1

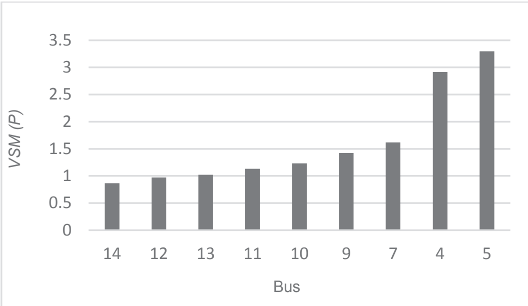

Fig. 6. *VSM (P)* by measuring the hypotenuse under the PV curve

Meanwhile, Table II lists the *VSM (Q)* values calculated based on (1) and by measuring hypotenuse under QV curve. These *VSM (Q)* values are also compared with the incremental values of Q load, *ΔQ*. The *ΔQ* stands for the maximum value of Q load that can be increased before the system experiencing voltage instability. Thus, to facilitate the observation process, Fig. 7 illustrates the ΔQ from the lowest to the highest value.

Based on Table II and Fig. 7, Bus 14 has the lowest value of *ΔQ* compared to the rest of the buses. This means Bus 14 is the weakest bus in the IEEE-14 bus system since it cannot afford high incremental value of Q load. In addition, the Q modal analysis technique that has been done in the previous research work [24,25] has also shown that Bus 14 has the highest tendency towards experiencing voltage instability compared to other buses in the system. Hence, more attention should be given to Bus 14 to make sure that it does not reach the voltage instability limit. Fig. 8 depicts VSM (Q) values calculated by using (1) is in an ascending order.

As can be seen in Fig. 8, Bus 13 is the weakest bus since it has the lowest *VSM (Q)* value. This is in contrast with the data listed in Table 2 and Fig. 7. Besides that, Fig. 8 also depicts that the *VSM (Q)* value of Bus 4 is similar to the *VSM (Q)* value of Bus 7. Whereas according to Fig. 7, Bus 4 can afford a huge amount of *ΔQ* value compared to Bus 7. This indicates that the *VSM (Q)* values calculated based on (1) are not in synchronisation with the values of ΔQ. Fig. 9 depicts *VSM (Q)* values calculated by measuring the hypotenuse under the QV curve in an ascending order.

TABLE II
VALUES OF *ΔQ* AND *VSM (Q)*

Bus	*ΔQ* (per unit)	*VSM (Q)* based on (1)	*VSM (Q)* by measuring the hypotenuse under the QV curve
4	2.5	0.9930	2.5501
5	2.7	1.0311	2.7321
7	1.2	0.9754	1.3299
9	1.1	0.9084	1.1710
10	0.9	0.8841	1.0230
11	0.8	0.8039	0.9641
12	0.7	0.9404	0.8699
13	0.8	0.8011	0.9574
14	0.6	0.8204	0.7897

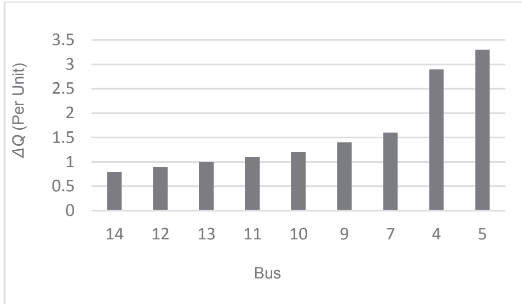

Fig. 7. The maximum value of Q load that can be increased before experiencing voltage instability

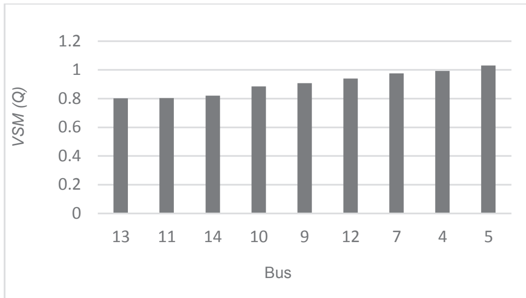

Fig. 8. VSM (Q) values based on (1)

Fig. 9 depicts that Bus 14 is the weakest bus in the IEEE-14 bus system since it has the lowest VSM (Q) value. This is in similar with the data in Fig. 7 and in [24]. In addition, it is observable from Fig. 9 that the ranking of the load buses from the weakest to the strongest are same with the ranking in Fig. 7. This proves that the VSM (Q) values calculated by measuring hypotenuse under QV curve are in synchronisation with the values of ΔQ.

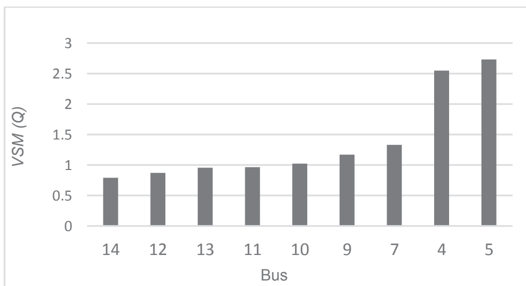

Fig. 9. *VSM (Q)* by measuring the hypotenuse under the QV curve

IV. Conclusion

Voltage instability analysis is an important parameter for monitoring the bus voltage in the electrical power system. Both *VSM (P)* and *VSM (Q)* values are very useful in showing the distance of how far the power system can run before experiencing voltage instability. A load bus is considered weak if it cannot accept high increased in load. Hence, the values of VSM should be in synchronization with the values of load increment. The research conducted in this paper has successfully showed that the calculation of VSM values by measuring the hypotenuse under PV and QV curves can give better results compared to the previous method. The VSM values calculated by measuring hypotenuse under PV and QV curves are in synchronizations with the load incremental values. In addition, the results have shown that the value of real power (P) at load busses can be increased much more compared to the value of reactive power (Q) of load. increased in reactive power (Q) of load give higher contributions towards voltage instability compared to the increased in real power (P) of load. It is very vital to perform voltage instability analysis especially the calculation of VSM values. This is because accurate VSM values are important to determine the weakest load bus of the power system. Once the weakest load bus has been determined, action can be taken to avoid voltage instability from taking place. The voltage instability has the capability to cause total system black-out. The black-out area caused by voltage instability might spread to one area or even worse, to the whole nation. This can lead to much worse problem especially to the economy.

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